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Tackling environmental impacts in simple trigeneration systems operating under variable conditions

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Abstract
Purpose Environmental concerns have been a growing issue when planning energy supply systems for buildings, as the energy demands (presenting seasonal and daily variations) represent one of the most energy-intensive consumptions in industrialized societies. The optimal operation corresponding to different energy demands of a trigeneration system was analyzed by an integrated methodology combining Thermoeconomic analysis and life cycle assessment, in order to adequately allocate the energy resources and the generated environmental loads to the different energy services produced.
Methods Thermoeconomic analysis, which is usually used to allocate energy and economic costs, is herein applied to the evaluation of environmental costs and distribution of resources throughout the trigeneration system. Attention is focused on the correct allocation of energy resources and environmental loads to internal flows and final products. Appropriate rules were established to calculate energy and environmental costs.
Results and discussion Operation of the system considered the possibilities that surplus electricity could be exported to the national grid and part of the cogenerated heat could be wasted if this resulted in a decrease of operation costs and/or environmental loads. The results obtained show a low-cost and low-emission production with respect to the separate production in different operation modes. It was observed that, in specific periods, the trigeneration system operates wasting part of the cogenerated heat, and, in other periods, part of the electricity produced is exported to the electric grid. The trigeneration system operates in these modes because it results beneficial from environmental or economic viewpoints, achieving a lower economic cost or fewer CO_2 emissions.
Conclusions The methodology presented as well as the allocation method proposal were congruent with the objectives of installing trigeneration systems that supplied energy services with fewer emissions than those of separate production and of equally benefitting the consumers of heat, coolth ("coolth" is used as the noun form of "cool"; opposite of warmth. Not to be confused with cooling, which is the opposite of heating.) (alias cooling energy), and electricity.

Keywords Allocation of environmental loads · CHP · CO_2 allocation · LCA · Thermoeconomics · Trigeneration

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1 Introduction

Modern society's increasing comfort demands leads to higher consumption of energy services in buildings (e.g., an increase in the use of air conditioning). Energy consumption of buildings in developed countries comprises 20–40 % of total energy use and is greater than industry and transportation figures in the European Union and USA (Pérez-Lombard et al. 2008). Usually, such high levels of energy consumption are counterbalanced by environmental tension regarding depletion of fossil fuels and an overall more rational use of energy. European research projects (CHOSE 2001; TRIGEMED

2003; Lamers 2008) agree on the significant potential of implementing trigeneration systems in the residential–commercial sector of countries in the Mediterranean area. The increase in energy conversion efficiency is, without doubt, the main advantage of producing different energy services (heat, coolth, and electricity) in one installation from the same energy source. The savings in energy resources consumed provides a three-way win: a reduction in consumer costs, enhancement of energy security supply, and reduced emissions (Chicco and Mancarella 2007; Serra et al. 2009).

Advantages of trigeneration systems in buildings have been demonstrated in literature, as the improved use of fuel is associated with economic savings and sparing of the environment, as less fuel is consumed and consequently less pollution is generated (Maglorie et al. 2002; Chicco and Mancarella 2008). In a conventional system, electricity is purchased from the grid for electricity and coolth, and heat is produced by an auxiliary boiler. Specifically, reductions of ≈30 % were obtained in total annualized cost (operation of the system plus equipment) when installing a trigeneration system instead of a conventional system in Lozano et al. (2009a), and differences of ≈38–55 % were achieved in favor of trigeneration when comparing the operational emissions (kg CO_2/h) with a conventional system (Carvalho et al. 2012). Similar results, however, slightly less optimistic, were found by Buoro et al. (2012). Therefore, substantial economic (Suamir et al. 2012) and energetic savings (Kong et al. 2004; Henning et al. 2007; Ebrahimi et al. 2012), as well as significant reduction of emissions (Lin et al. 2007), can be accomplished using a properly integrated energy system when compared with conventional energy systems providing the same quality of energy services.

In multiproduct systems, it is often crucial to determine the adequate cost of final products, which in the case of trigeneration systems are the energy services supplied. Allocation of costs is the evaluation of resources consumed/used for obtaining the different products, i.e., in the case of a trigeneration system, the evaluation of the energy costs of the final products consists in evaluating the amount of the energy fuel plant consumed in the production of each energy service (power, heat, and coolth). If the environmental burden provoked by the resources' consumption is known, as well as the allocation of the resources to the final products, it is also possible to assess the environmental loads corresponding to the production of each energy service of the trigeneration system. Allocation of costs in cogeneration and trigeneration systems is important because the adequate allocation of resources is fundamental to attribute the correct share of costs (as well as environmental burden, e.g., CO_2 emissions) to each energy service. A key aspect in the acceptance and success of trigeneration systems (seen as more complex but more efficient) by the users is that no unfair share of resources occurs. If the consumer assesses that the allocation was fair, the buy-in is more likely to occur.

The idea behind knowledge on the costs or environmental impacts of an energy service is that the consumer can make an informed decision on which energy services to utilize based on the share of resources attributed through the allocation proposal. If the consumer considers that all benefits are allocated rationally and in an equitable manner among the co-products, he/she will be more inclined to consume, especially if the final information shows the product is environmentally friendly or more economic.

While considerable research has been published on the topic of cost allocation, the specific environmental load allocation problems faced in trigeneration systems have not been formally addressed. Most existing studies on cost allocation in cogeneration systems have focused on systems operating at nominal load, isolated from the economic environment, and with an elevated self-consumption of products (including all cogenerated heat). This work addresses the issue of allocating economic costs and environmental loads in trigeneration systems for the residential–commercial sector. In addition, the possibilities of purchase/sale of electricity with the support of an auxiliary boiler and waste of part of the cogenerated heat were also considered. Economic and environmental costs were determined for all internal flows and final products, and in different operation modes, through the application of the thermoeconomic analysis methodology.

This article shows how the thermoeconomic analysis methodology, usually used to allocate energy and economic costs, can be applied also in the allocation of environmental costs (evaluated by applying the life cycle assessment methodology). Attention is focused on the correct allocation of the energy resources consumed and of the environmental loads involved in the operation of the trigeneration system to internal flows and final products. To this end, several examples were considered corresponding to different operation modes of the system. The objective consists of determining appropriate rules to evaluate energy and environmental costs, through the application of thermoeconomic analysis. For each operation mode, energy and environmental costs were obtained through the application of the same methodology. The analysis of energy and environmental costs highlights the validity of the thermoeconomic approach to carry out the allocation of energy, economic, and environmental resources.

1.1 Allocation in LCA

Consideration of environmental impacts when designing energy supply systems has been in the spotlight due to more stringent requisites for reductions of emissions as a consequence of a higher level of environmental conscience. Life

cycle assessment (LCA) is a tool that provides a global perspective of environmental loads and has the potential to fulfill the need for an adequate design tool for energy supply systems (Guinee 2002). LCA identifies and quantifies the use of mass and energy as well as environmental emissions, allowing for the evaluation and comparison of environmental improvement strategies. The *life cycle* or *cradle-to-grave* impacts include those resulting from extraction of raw materials, fabrication of the product, transportation or distribution of the product to the consumer, use of the product by the consumer, and disposal or recovery of the product after its useful life (Carvalho 2011). Environmental costs can be understood as a category of cost (according to the generation of environmental loads in order to obtain a flow; Carvalho et al. 2012).

Allocation is defined as the procedure of assigning the environmental burdens generated by a process to its functions or products. In practice, allocation plays a major role in cogeneration energy supply systems, since the supply of each of the energy services is supported by several subsystems, which are partly used by that service. The issue is which part of the environmental burden of the subsystem must be allocated to a specific service. From this perspective, the allocation issue in multiproduct energy systems is how to determine the amount of environmental burden that should be apportioned to each energy product or service. Some solutions have been suggested and applied to the allocation problem in cogeneration systems (Rosen 2008; Aldrich et al. 2001; Reap et al. 2008) but, when applied to trigeneration systems, proved to be unfair in terms of distribution of emissions (Carvalho 2011).

Obviously, arbitrary allocations could lead to incorrect LCA results and less-preferable decisions based on these results. Allocation in joint production has the distinction of being called one of the unresolved and often discussed methodological issues in life cycle inventory analysis (Azapagic and Clift 1999; Heijungs and Frischnecht 1998; Ekvall and Finnveden 2001). ISO recommends that LCA practitioners follow a stepwise procedure (Ekvall and Finnveden 2001) to deal with the allocation problem. More recently, in a review of allocation approaches, Curran (2007) concluded that no single method provides a general solution. Frischknecht (2000) gives well-founded reasons why value judgements may be involved in allocation of joint production and proposes a classification of allocation situations based on three main distinctive features: (1) separated/combined/joint production, (2) one/several decision makers, and (3) competitive/monopolistic market. In separated production, there is no problem at all. In combined production, physical causal relationships may be used to identify adequate allocation factors, something which is impossible in joint production. Individual decision makers may solve their allocation problem in line with their objectives, whereas a group of distinct decision makers needs to pay regards to each other (Wepfer 1980).

1.2 Thermoeconomic cost accounting

Thermoeconomics is an energy analysis tool that has been used to support the design, synthesis, and operation of energy systems by providing crucial information not available through conventional analyses (Carvalho 2011). Thermoeconomics combines economic and thermodynamic analysis with the purpose of revealing opportunities of energy and cost savings when designing and operating energy conversion systems (Gaggioli 1983; Lozano and Valero 1993; El-Sayed and Gaggioli 1989). The starting point of thermoeconomics is thermodynamics. In accordance with thermodynamics, all real processes consume a determined amount of energy resources that can be identified and quantified. Economics provides the concept of cost, which represents the value of the resources consumed to obtain a product or service. A basic concept of thermoeconomic analysis is the energy cost, understood as the value of resources consumed in order to obtain a piece of equipment, produce a mass and/or energy flow, supply a service, etc. Therefore, the unit energy cost of a flow represents the amount of resources that must be supplied to the system in order to obtain one unit of such flow. Unit costs are used by analytic accounting thermoeconomic methods to allocate rational prices to the final products of energy systems and to follow the cost formation process throughout the system, from the consumption of energy resources until the final products.

The criterion utilized to determine the unit costs of internal flows and final products of energy supply systems is a key aspect and distinguishable among the different thermoeconomic analysis methods (Tsatsaronis 1993; Lazzaretto and Tsatsaronis 2006; Reistad and Gaggioli 1980). The difficulty of cost allocation is greater when the same system utilizes common resources to produce several products of different nature and/or with different uses. Cost allocation is important because it will influence the behavior of consumers through the stimuli received from a higher/lower value assigned to the products. Different cost allocation criteria have been proposed for cogeneration systems (Araujo and Nebra 1999; Abusoglu and Kanoglu 2009; Lucas 2000). Although traditionally used to quantify and assess the economic and energy (exergy) resources consumed, there is no limitation to apply the methodology of thermoeconomic analysis to assess also the environmental load or impact of the resources consumed (Gonzalez et al. 2003; Lozano et al. 2009b).

1.3 Methodological proposal

This investigation shows how to apply thermoeconomic analysis to evaluate costs of different nature, as for example energy, economic, or environmental costs in trigeneration

systems. When these systems serve the residential–commercial sector, the operation mode is clearly determined by the economic environment, by the possibilities of purchasing/selling electricity from/to the electric grid, and by a great daily and seasonal variability in energy demands. A rational distribution of cost to the product, which comprehends the nature of the optimal operation mode (Lozano et al. 2009c), will promote rational and efficient energy services production and consumption. Moreover, the systematic evaluation of the cost of representative internal flows of a system allows the cost formation process of its products to be known, i.e., how the consumed resources (economic, energy, and environmental) are distributed throughout the productive process.

This task requires the application of rules, common to all thermoeconomic approaches, such as (a) conservative cost balance for each piece of equipment and (b) allocation of the same unit cost to homogeneous products (final or internally consumed) originated from the same flow. It is also necessary to tackle new issues, still not addressed by existing methods, such as (c) rational allocation of joint production costs to the final products of trigeneration systems.

According to Carvalho (2011), thermoeconomic analysis techniques and LCA are both based on the premise that all of the resources required for producing a good or service need to be accounted for. Thermoeconomics is usually applied to energy production plants and the limits of the system are those of the associated plant. However, there is no constraint that impedes widening the limits of analysis to include the well or the mine from where the natural resources were extracted. Usually in LCA, only the inputs and outputs are measurable in the system under analysis (black box analysis). Applying the philosophy of thermoeconomics to energy production plants opens this black box and unravels the process of environmental burden formation, which is where the importance of combining thermoeconomics with LCA lies (Carvalho et al. 2012). In parallel with the energy cost formation process in thermoeconomics, it will be possible to evaluate the environmental cost formation process, associated with the consumption of natural resources, and determine the distribution of environmental loads throughout the system, i.e., evaluate the formation process of environmental costs in the productive system from the consumption of natural resources until the formation of final products (Carvalho 2011).

The main purpose of this work consists on presenting how the methodology of thermoeconomic analysis, which is usually used to allocate energy and economic costs, can also be applied to the allocation of environmental costs and analysis of generation of environmental burden in a productive system. Starting from the analysis of the coproduction nature in a simple trigeneration system, seeking clarity in the comprehension of concepts, an allocation method is proposed based on thermoeconomics. The proposal is congruent with the objective of providing energy services with fewer emissions and costs in an optimized trigeneration system than those of separate production, equally benefitting the consumers of different energy services (heat, coolth, and electricity).

2 Trigeneration system

Trigeneration can be defined as the simultaneous production of three energy services (e.g., electricity, heat, and coolth), from common resources. The trigeneration system must match all different energy service demands (electricity, E_d; heat, Q_d; and coolth, R_d) of a consumer center. A simple trigeneration system basically consists of a cogeneration module and an absorption chiller.

The description of the simple trigeneration system subject of analysis follows (Lozano et al. 2009c): the cogeneration module (CM) includes a prime mover (e.g., reciprocating engine) to convert fuel energy to shaft power, an alternator to transform mechanical power to electrical power, and a heat recovery system. The absorption chiller (AC) can produce cooling from the recovered heat. Trigeneration plants become distinguishable by the different additional equipment incorporated (Wu and Wang 2006; Deng et al. 2011). Figure 1 shows the simple trigeneration system herein analyzed, which also includes a mechanical chiller (EC) driven by electricity and a fuel oil-fired auxiliary boiler (AB), in order to provide, when required, the demanded coolth and heat not produced by the cogeneration module.

Selection of equipment took into account input/output utility flows based on appropriate energy process integration, which is a key concept and a fundamental characteristic of an optimized trigeneration system, and justifies the need to conduct the analysis herein presented on the allocation of environmental loads (or resources, in general). The simple trigeneration system shown in Fig. 1 is proposed considering

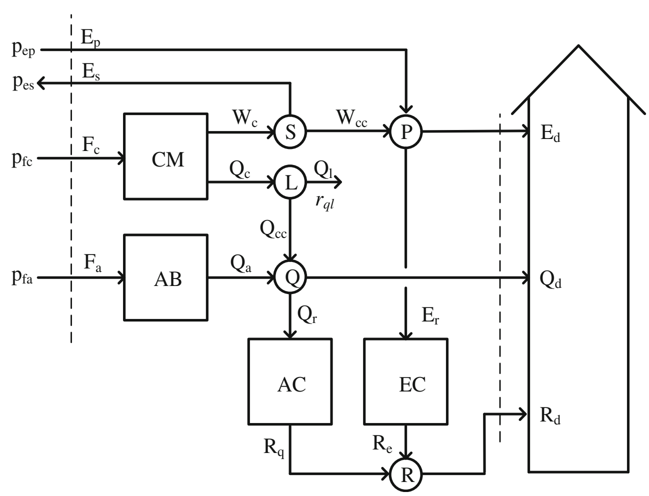


Fig. 1 Simple trigeneration system

heat and power sources (reciprocating gas engine, hot water boiler). Also considered were the requirements—heat, power, and cooling—of (1) the energy services demanded by the consumer center, e.g., a multifamily building and (2) different pieces of equipment. Heat integration methodologies are particularly powerful tools that should be included in the synthesis of trigeneration systems. In this respect, a broader perspective on the consideration of heat integration in the configuration of a polygeneration system is presented in Serra et al. (2009), where energy process integration is shown to encompass techniques based on the thermodynamic and economic analysis of individual components as well as the system as a whole, oriented to design and improve production systems, maximizing the efficiency of consumed resources. The fundamentals of energy process integration are found in exergy analysis, pinch analysis, and in the mathematical optimization techniques applied to process synthesis.

Table 1 shows technical data for the different pieces of equipment that constitute the simple trigeneration system.

Following Lozano et al. (2009a), the energy demands of the consumer center will always be met either by the productive units of Table 1 or with the help of purchased electricity from the electric grid (E_p). There is also the possibility of selling cogenerated electricity (E_s) to the electric grid. A fraction (Q_l) of the cogenerated heat can be dumped (wasted) into the environment. Waste heat allows for the operation of the cogeneration module to match the demand of the consumer center or to realize profits by selling surplus electricity to the market. F_c and F_a refer to the fuel consumed by the cogeneration module and the auxiliary boiler, respectively. The environmental loads associated with the operation of the system are generated in the cogeneration module, which consumes natural gas, and in the auxiliary boiler, which consumes fuel oil. The environmental loads associated with the electricity purchased and sold to the electric grid have also been taken into consideration.

The system interacts with the economic environment (market) through the purchase of natural gas, fuel oil, and electricity, as well as through the sale of cogenerated electricity. The prices of the energy flows interchanged with the market are shown in Table 2.

Table 1 Technical parameters of the equipment of the simple trigeneration system

Equipment	Efficiency coefficient	Nominal capacity (kW)
Cogeneration module	$\alpha_w \equiv W_c/F_c = 0.35$ $\alpha_q \equiv Q_c/F_c = 0.40$	$W_{c\ nom} = 350$
Auxiliary boiler	$\eta_q \equiv Q_a/F_a = 0.80$	$Q_{a\ nom} = 400$
Absorption chiller	$COP_q \equiv R_q/Q_r = 0.625$	$R_{q\ nom} = 250$
Mechanical chiller	$COP_e \equiv R_e/E_r = 5.0$	$R_{e\ nom} = 250$

Table 2 Energy prices (€/kWh)

Purchased electricity	Sold electricity	Natural gas	Fueloil
$p_{ep} = 0.100$	$p_{es} = 0.080$	$p_{gn} = 0.025$	$p_{fa} = 0.020$

The only environmental loads considered herein were the emissions of CO_2. The software SIMAPRO (2012), a specialized LCA tool, was utilized to calculate the emissions associated with fuels and electricity, which are shown in Table 3 (Carvalho 2011). The emissions associated with the interchange of electricity with the electric grid depend on the generation mix used in the zone where the cogeneration plant is located. In this work, it is considered that the grid is supplied by coal power plants (Carvalho 2011). A brief explanation on how the environmental loads were calculated can be found in Appendix 1 (Electronic Supplementary Material).

A linear programming model was built and solved to obtain the optimal operation state in function of the energy service demands. The objective function for the optimization procedure is defined in economic terms, expressed as the minimum cost of meeting the energy demands, HC (in €/h)

$$\mathrm{HC} = p_{fc} \cdot F_c + p_{fa} \cdot F_a + p_{ep} \cdot E_p - p_{es} \cdot E_s \quad (1)$$

where the coefficients of the objective function (energy prices) are taken from Table 2.

When the system is operated under the environmental optimal, the objective function to minimize is the flow of CO_2 emissions, HEC (in kg/h)

$$\mathrm{HEC} = p_{fc} \cdot F_c + p_{fa} \cdot F_a + p_{ep} \cdot E_p - p_{es} \cdot E_s \quad (2)$$

where now the coefficients of the objective function (environmental costs) are taken from Table 3.

Therefore, the optimization problem consists of minimizing the objective function HC or HEC, in accordance with the desired objective, subject to production restrictions of the equipment, efficiency of the energy transformation processes occurring in the equipment, and to energy balances, which have been presented in detail in previous works (Carvalho 2011; Lozano et al. 2009c).

Considering all combinations of purchased electricity (E_p), sold electricity (E_s), auxiliary heat (Q_a), and waste heat (Q_l), the resulting feasible operation states could be classified into nine different operation modes. These operation modes

Table 3 Environmental costs of the interchanged energy flows (kg CO_2/kWh)

Purchased electricity	Sold electricity	Natural gas	Fuel oil
$p_{ep} = 1.020$	$p_{es} = 1.020$	$p_{gn} = 0.272$	$p_{fa} = 0.305$

corresponded to different demands of the energy services of the consumer center and are shown in Table 4.

Table 5 shows a summary of results (demand, flows, and hourly cost) obtained for four examples that corresponded to the most relevant operation modes (indicated in bold in Table 4). In the four examples, the optimal economic operation state coincides with the optimal environmental operation states. The results were obtained with the optimization tool LINGO (2008). As a result of the optimization, the cogeneration system operates at full load in these cases. In Table 5, numbers in bold indicate purchased electricity (E_p), sold electricity (E_s), auxiliary heat (Q_a) and waste heat (Q_l), which in Table 4 aid in the establishment of different operation modes.

Results in Table 5 were obtained considering a single-fuel representative coal power plant (1.020 kg CO_2/kWh). Previous results obtained with the environmental minimizations using the Spanish electricity mix[1] (0.385 kg CO_2/kWh, in Carvalho 2011) presented very different results when compared with the economic minimization (Lozano et al. 2009b). Economic minimization always suggested the cogeneration module operated at full load, even if wasting part of cogenerated heat. However, environmental minimizations suggested the cogeneration module operate at part load or not operate at all. Following Carvalho (2011), changes in the origin of the electricity supplied by the grid will affect the results of the optimization: emissions above 0.777 kg CO_2/kWh result in operating the cogeneration module at full load. After verification of each single contributor to the Spanish electricity mix, a single-fuel coal power plant was chosen to supply electricity to the grid. With this change, it was always interesting to operate the cogeneration module, even if a part of cogenerated heat was wasted. The results of Buoro et al. (2013) corroborate the fact that electricity produced by CHP units is environmentally more convenient when the carbon intensity of grid electricity is higher.

3 Thermoeconomic analysis and cost allocation

In accordance with the classification of allocation situations proposed by Frischknecht (2000), the trigeneration system analyzed here presents: (i) several decision makers—the consumers are also the owners of the system and are interested in sharing the benefits obtained from the more efficient production, (ii) the market has established prices for the energy flows interchanged, and (3) joint production—the relationship between the products of the cogeneration module is constant, even at partial loads.

Identification of the correct productive structure of the energy supply system constitutes an indispensable condition for a correct thermoeconomic analysis. In the case of the simple trigeneration system considered herein, Fig. 2 shows the trigeneration subsystem representing the nucleus of the system, i.e., the set of equipment where concurrent production of energy services takes place. The trigeneration subsystem is composed of the cogeneration module (producing electricity and heat) and absorption chiller (when utilized to produce cooling from cogenerated heat). In this subsystem, common energy resources are consumed for the concurrent production of energy services, which is achieved through the energy integration of the processes taking place in the system. Such a high level of integration hinders the establishment of a unique distribution of the resources consumed towards the products obtained. In other words, as a consequence of energy integration, it is not possible to determine the amount of resources consumed in the production of each energy service. Therefore, there are several options to allocate the fuel consumed in the cogeneration module, F_c, to the different energy products obtained (Q_{cq}, R_{qc}, and W_{cc}). A rational distribution of the fuel consumed will promote efficient production and

[1] 25.8 % coal, 24.4 % natural gas—combined cycle—19.7 % nuclear, 10.4 % others (biomass, natural gas—cogeneration—minihydraulic), 9.4 % eolic, 9.4 % hydraulic, and 0.9 % fuel gas.

Table 4 Operation modes of the trigeneration system

	E_p>0 and E_s=0	E_p=0 and E_s=0	E_p=0 and E_s>0
Q_a>0 and Q_l=0	**C_1**	C_4	**C_7**
Q_a=0 and Q_l=0	C_2	C_5	C_8
Q_a=0 and Q_l>0	**C_3**	C_6	**C_9**

Table 5 Energy flows (kW) for four optimal operation states for the analyzed system

	ExC1	ExC3	ExC7	ExC9
E_d	400	400	200	200
Q_d	400	100	600	100
R_d	400	100	100	100
E_p	**100**	**50**	0	0
E_s	0	0	**130**	**150**
F_c	1,000	1,000	1,000	1,000
F_a	300	0	250	0
W_c	350	350	350	350
Q_c	400	400	400	400
W_{cc}	350	350	220	200
E_r	50	0	20	0
Q_l	0	**140**	0	**140**
Q_{cc}	400	260	400	260
Q_a	**240**	0	**200**	0
Q_r	240	160	0	160
R_q	150	100	0	100
R_e	250	0	100	0
HC Operation cost (€/h)	41.00	30.00	19.60	13.00
HEC CO_2 emissions (kg/h)	465.50	323.00	215.65	119.00
Operation mode	C_1	C_3	C_7	C_9

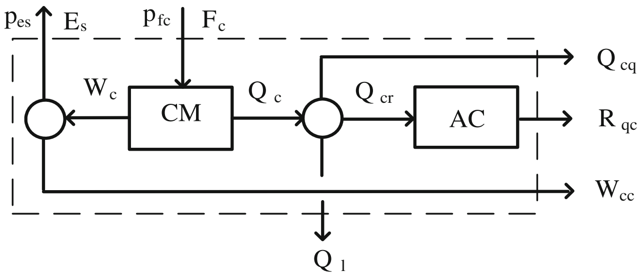


Fig. 2 Trigeneration subsystem

consumption and low environmental impact of the energy services. To this end, the nature of the optimal operation mode must be known and taken into account (Lozano et al. 2009c).

In the trigeneration subsystem, a part of the electricity produced can be fed into the national electrical grid, E_s, and the remaining, W_{cc}, is consumed internally by the trigeneration system or supplied to the consumer center. In the case of heat, there are three possible destinations: (1) match the heat demand, Q_{cq}; (2) produce cooling in the absorption chiller, R_{qc}; and (3) be wasted into the environment, Q_l. With the objective of simplifying the mathematical approach, without losing generality in the analysis, the cost of waste heat has been considered zero in this work. Therefore, W_{cc}, Q_{cq}, and R_{qc} are the three cogenerated products to which it is necessary to allocate costs, i.e., a determined amount of consumed resources.

In the simple trigeneration system herein analyzed (see Fig. 1), there is also an auxiliary boiler and a mechanical chiller, to support the production of the trigeneration subsystem when necessary. This fact must be taken into account at the time of allocating internal flow and cogenerated product costs. In this way, when the cogeneration module and the auxiliary boiler are operating jointly, as occurs in examples ExC1 and ExC7, the share of consumed cogenerated heat Q_{cc} must be determined, (i.e., $Q_c - Q_l$) that satisfies the demand of the consumer center, Q_{cq}, and the share of cogenerated heat utilized to produce cooling in the absorption chiller, R_{qc}. Analogously, the heat produced by the auxiliary boiler, Q_a, can be used either to cover the heat demand of the consumer center, Q_d, and/or match the necessary heat to drive the absorption chiller, Q_r.

The productive structure obtained in consequence of these considerations is shown in Fig. 3, where the conceptual division of the absorption chiller into two virtual absorption chillers can be seen. Each virtual absorption chiller is associated to one of the thermal energy flows consumed: cogenerated heat, Q_{cr}, and heat produced by the auxiliary boiler, Q_{ar}. The total heat driving the absorption chiller, Q_r in Fig. 1, is composed of these two virtual thermal energy flows

$$Q_r = Q_{cr} + Q_{ar} \tag{3}$$

This work considered no priority or technical limitation as the cogeneration module was able to independently provide, when required, heat to the consumer center or the absorption chiller. In addition, no priority or technical limitation was considered for the auxiliary boiler (independent provision, when required, of heat to the consumer center or the absorption chiller). Furthermore, the heat produced was proportionally allocated to the consumer center and the absorption chiller according to the total heat demanded by them.

In accordance with the previous premises, heat is allocated (a) between the consumer center and the absorption chiller in proportion to the heat demanded and (b) between the cogeneration system and the auxiliary boiler in proportion to the produced heat, which allows for the establishment of the following parameters:

$$\beta = Q_d \ (Q_d + Q_r) \tag{4}$$

$$\gamma = Q_{cc} \ (Q_{cc} + Q_a) \tag{5}$$

Therefore, the distribution of cogenerated heat can be quantified as

$$Q_{cq} = \beta \cdot Q_{cc} \tag{6}$$

$$Q_{cr} = (1-\beta) \cdot Q_{cc} \tag{7}$$

Analogously, the heat produced in the auxiliary boiler is distributed in accordance with

$$Q_{aq} = \beta \cdot Q_a \tag{8}$$

$$Q_{ar} = (1-\beta) \cdot Q_a \tag{9}$$

Coolth produced from cogenerated heat in the absorption chiller is

$$R_{qc} = \gamma \cdot R_q \tag{10}$$

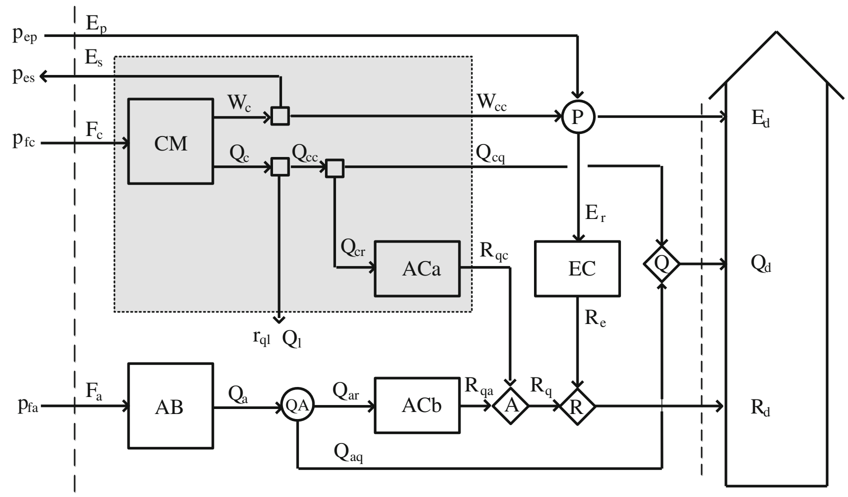
and the coolth produced from the heat produced in the auxiliary boiler is

$$R_{qa} = (1-\gamma) \cdot R_q \tag{11}$$

Combining the energy flows of Table 5 and the previous equations, the distribution of heat flows is obtained as shown in Table 6, where the numbers in italics indicate the energy demands of the consumer center.

Once the nature of coproduction and all relevant flows of the trigeneration system are defined and determined, it is then possible to allocate the consumed resources towards the different coproducts obtained. Considering the principle of an equal share of benefits among all the consumers, it is proposed to apply the same discount to all products of the trigeneration

Fig. 3 Productive structure of the trigeneration system



subsystem. This discount is calculated with a reference on the conventional separate production of the energy services

$$d = 1 - c_{wcc}\ (c_w)_{ref} = 1 - c_{qcq}\ (c_q)_{ref} = 1 - c_{rqc}\ (c_r)_{ref} \quad (12)$$

The reference costs utilized to calculate the discount corresponding to the energy costs are those corresponding to the separate production of energy services (refer to Table 2). In the case of electricity, the reference is the price of electricity purchased from the grid [$(c_w)_{ref}$]. For heat, the reference price is the cost of producing heat in the auxiliary boiler of the system, using fuel oil [$(c_q)_{ref}$]. For cooling, the reference is the conventional production of cooling, via mechanical chiller and using electricity purchased from the grid [$(c_r)_{ref}$].

$$(c_w)_{ref} = p_{ep} = 0.100\ \text{sf€}\ \ \text{kWh} \quad (13)$$

$$(c_q)_{ref} = p_{fa}\ \eta_q = 0.020\ 0.80 = 0.025\ \text{sf€}\ \ \text{kWh} \quad (14)$$

$$(c_r)_{ref} = p_{ep}\ \text{COP}_e = 0.100\ 5.0 = 0.020\ \text{sf€}\ \ \text{kWh} \quad (15)$$

Table 6 Heat flow distribution

		ExC_1	ExC_3	ExC_7	ExC_9
E_d	kW	*400*	*400*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*
γ		0.625	1	0.667	1
β		0.625	0.385	1	0.385
Q_{cq}	kW	250	100	400	100
Q_{cr}	kW	150	160	0	160
Q_{aq}	kW	150	0	200	0
Q_{ar}	kW	90	0	0	0
R_{qc}	kW	93.75	100	0	100
R_{qa}	kW	56.25	0	0	0

The reference costs utilized to calculate the discount corresponding to the environmental costs are the emissions associated with the separated production of energy services (refer to Table 3). For electricity, the reference is the emissions associated with the electricity purchased from the electric grid [$(c_w)_{ref}$]. For heat, the reference is the production of heat in the auxiliary boiler of the system, using fuel oil [$(c_q)_{ref}$]. For cooling, the reference is the conventional production of coolth, via mechanical chiller and using electricity purchased from the grid [$(c_r)_{ref}$].

$$(c_w)_{ref} = p_{ep} = 1.020\ \text{kg}\ CO_2\ \ \text{kWh} \quad (16)$$

$$(c_q)_{ref} = p_{fa}\ \eta_q = 0.305\ 0.80$$
$$= 0.38125\ \text{kg}\ CO_2\ \ \text{kWh} \quad (17)$$

$$(c_r)_{ref} = p_{ep}\ \text{COP}_e = 1.020\ 5.0 = 0.204\ \text{kg}\ CO_2\ \ \text{kWh} \quad (18)$$

4 Application to trigeneration system

This section applies the concepts explained in the previous section to obtain the energy and environmental (CO_2 emissions) costs corresponding to the internal flows and final products of the trigeneration system represented in Fig. 3.

As previously mentioned, the cost conservation principle, which is common to all thermoeconomic analysis methodologies, establishes that the costs of the resources consumed in an equipment or subsystem must be allocated to the useful products. In this way, the following cost balances are formulated

Equipment:

$$\text{CM} + \text{ACa}: \quad p_{fc}\cdot F_c - p_{es}\cdot E_s = c_{wcc}\cdot W_{cc} + c_{qcq}\cdot Q_{cq} + c_{rqc}\cdot R_{qc} \tag{19}$$

$$\text{AB}: \quad p_{fa}\cdot F_a = c_{qa}\cdot Q_a \tag{20}$$

$$\text{ACb}: \quad c_{qar}\cdot Q_{ar} = c_{rqa}\cdot R_{qa} \tag{21}$$

$$\text{EC}: \quad c_{er}\cdot E_r = c_{re}\cdot R_e \tag{22}$$

Distributors (circles):

$$\text{QA}: \quad c_{qa}\cdot Q_a = c_{qar}\cdot Q_{ar} + c_{qaq}\cdot Q_{aq} \tag{23}$$

$$P: \quad c_{wcc}\cdot W_{cc} + c_{ep}\cdot E_p = c_{er}\cdot E_r + c_{ed}\cdot E_d \tag{24}$$

Unions (rhombuses):

$$Q: \quad c_{qcq}\cdot Q_{cq} + c_{qaq}\cdot Q_{aq} = c_{qd}\cdot Q_d \tag{25}$$

$$A: \quad c_{rqc}\cdot R_{qc} + c_{rqa}\cdot R_{qa} = c_{rq}\cdot R_q \tag{26}$$

$$R: \quad c_{rq}\cdot R_q + c_{re}\cdot R_e = c_{rd}\cdot R_d \tag{27}$$

Following Lozano et al. (2009c), considering that the operation state of the plant was known, then, all energy flows (see Tables 5 and 6) were also known. Consequently, there were 13 unit costs of internal flows and final products to be calculated: c_{wcc}, c_{qcq}, c_{rqc}, c_{qa}, c_{qar}, c_{qaq}, c_{rqa}, c_{rq}, c_{er}, c_{re}, c_{ed}, c_{qd}, and c_{rd}. The cost balances provide nine equations, and therefore, it is necessary to define four additional auxiliary equations that allow for the determination of the unit costs of the internal flows and final products of the system.

In the distributor QA, corresponding to the heat produced by the auxiliary boiler, the following equation is formulated

$$\text{QA}: \quad c_{qar} = c_{qaq} \tag{28}$$

In the distributor *P*, the cogenerated electricity and the electricity purchased from the electric grid are combined, and then distributed without preferences, i.e., with the same unit cost to satisfy the demand of the consumer center and of the mechanical chiller

$$P: \quad c_{er} = c_{ed} \tag{29}$$

In these two distributors, QA and *P*, an accepted rule was applied, establishing that the unit cost of several flows obtained from a homogeneous flow is the same.

Finally, two more auxiliary equations are needed. These equations will define how the environmental loads or energy costs will be allocated to the coproduced energy services in the trigeneration subsystem. Considering the coproduction nature explained in the previous section, these equations must attribute the same discount d (see Eq. 12) to the energy costs or environmental loads distributed among the consumers. In accordance with this premise, the proposed auxiliary equations are

$$c_{qcq} \ (c_q)_{ref} = c_{wcc} \ (c_w)_{ref} \tag{30}$$

$$c_{rqc} \ (c_r)_{ref} = c_{wcc} \ (c_w)_{ref} \tag{31}$$

It must be highlighted that the heat produced in the cogeneration module receives two different unit costs. The heat used to satisfy the heat demand, Q_{cq}, received a discount with respect to the production of heat in a conventional boiler, and the heat used for coolth production, Q_{cr}, received a discount with respect the conventional production of coolth in a mechanical chiller. Equations 25 and 26, which explain the unit cost of the heat demanded and of the absorption cooling in function of its procedence, can be expressed as

$$c_{qd} = c_{qcq}\cdot\gamma + c_{qaq}\cdot(1-\gamma) \tag{32}$$

$$c_{rq} = c_{rqc}\cdot\gamma + c_{rqa}\cdot(1-\gamma) \tag{33}$$

Utilizing the equation system (19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, and 31), the prices of energy resources shown in Table 2, and the reference costs of equations (13, 14, and 15), the values of the energy costs (expressed in monetary units) were obtained and shown in Table 7. The values of the environmental costs were obtained (Table 8) from the combination of environmental unit costs of interchanged energy flows (Table 3), reference costs of equations (16, 17, and 18), and the equation system (19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, and 31). In tables 7 and 8, the numbers in italics refer to the energy demands of the consumer center.

From the values allocated to the energy costs of Table 7 it was verified that the costs attributed to the final products (c_{ed}, c_{qd}, and c_{rd}) are lower than the costs of the electricity purchased from the grid, heat produced in the auxiliary boiler, and coolth produced in a mechanical chiller (Eqs. 13, 14, and 15). In the case of the environmental costs, it can be observed in Table 8 that in all cases, the values of the environmental costs of (CO_2 emissions corresponding to) the final products (c_{ed}, c_{qd} and c_{rd}) are also lower than the environmental costs of (CO_2 emissions corresponding to) the electricity purchased from the grid, heat produced in the auxiliary boiler, and cooling produced via mechanical chiller (Eqs. 16, 17, and 18).

Different allocation methods of environmental loads to electricity and heat products were found in the literature (Aldrich et al. 2001; Reap et al. 2008; Rosen 2008; Carvalho 2011). However, the main issue is that simple methods focus on the immediate products of the cogeneration module, not accounting for possible different destinations or

Table 7 Economic costs of internal flows and final products

		ExC_1	ExC_3	ExC_7	ExC_9
E_d	kW	*400*	*400*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*
d		0.420	0.367	0.544	0.469
c_{wcc}	€/kWh	0.05797	0.06329	0.04563	0.05306
c_{qcq}	€/kWh	0.01449	0.01582	0.01141	0.01327
c_{rqc}	€/kWh	0.01159	0.01266	–	0.01061
c_{qa}	€/kWh	0.02500	–	0.02500	–
c_{rqa}	€/kWh	0.04000	–	0.04000	–
c_{rq}	€/kWh	0.02225	0.01266	–	0.01061
c_{re}	€/kWh	0.01346	–	0.00913	–
c_{ed}	€/kWh	0.06731	0.06788	0.04563	0.05306
c_{qd}	€/kWh	0.01843	0.01582	0.01594	0.01327
c_{rd}	€/kWh	0.01676	0.01266	0.00913	0.01061

uses. Existing simple allocation methods were tested in Carvalho (2011) with the optimization model presented herein: allocation based on energy, exergy, fuel chargeable to power, and allocation based on separate production. The allocation method can influence whether the consumer will consume products of the trigeneration system, and the choice of one method over another will depend on the objective of the study. These existing methods produced final emissions that would lead consumers of heat or electricity to wrongly to believe that they were consuming lower carbon supplies than from non-CHP alternatives or vice versa.

Therefore, the herein proposed cost allocation rules (environmental assessment rules) provided values coherent with the objective of benefitting the consumers of the energy services produced by an optimized and efficient trigeneration system; this benefit is the more efficient and environmentally friendly concurrent production in comparison to obtaining each energy service separately through conventional systems.

Table 8 Environmental costs of internal flows and final products

		ExC_1	ExC_3	ExC_7	ExC_9
E_d	kW	*400*	*400*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*
d		0.423	0.345	0.630	0.547
c_{wcc}	kg CO_2/kWh	0.58850	0.66769	0.37726	0.46236
c_{qcq}	kg CO_2/kWh	0.21997	0.24956	0.14101	0.17282
c_{rqc}	kg CO_2/kWh	0.11770	0.13354	–	0.09247
c_{qa}	kg CO_2/kWh	0.38125	–	0.38125	–
c_{rqa}	kg CO_2/kWh	0.61000	–	0.61000	–
c_{rq}	kg CO_2/kWh	0.30231	0.13354	–	0.09247
c_{re}	kg CO_2/kWh	0.13688	–	0.07545	–
c_{ed}	kg CO_2/kWh	0.68439	0.71172	0.37726	0.46236
c_{qd}	kg CO_2/kWh	0.28045	0.24956	0.22109	0.17282
c_{rd}	kg CO_2/kWh	0.19892	0.13354	0.07545	0.09247

The results obtained show a low-cost and low-emission production with respect to the separate production (see Eqs. 13, 14, 15, 16, 17, and 18) in different operation modes. It was observed that in specific periods the trigeneration system operates wasting part of the cogenerated heat (ExC_3 and ExC_9), and in other periods, part of the electricity produced is exported to the electric grid (ExC_7 and ExC_9). The trigeneration system operates in these modes because it results beneficial from environmental or economic viewpoints, achieving a lower economic cost or fewer CO_2 emissions. Therefore, the benefits corresponding to the sale of electricity and the inefficiencies associated with the waste of heat must be allocated rationally and equally among the cogenerated products (coproducts). The allocation rules distributed all the benefits and inefficiencies associated with the concurrent production among the three coproducts obtained (electricity, heat, and coolth) in an equitable manner.

5 Conclusions

When a system produces different products, the issue of cost allocation arises: This is important because cost allocation not only affects the cost of products but also the behavior of consumers. Most of existing studies on cost allocation in cogeneration systems have focused on systems operating at nominal load, isolated from the economic environment, and with an elevated self-consumption of products (including all cogenerated heat).

This work has addressed the issue of allocating economic costs and environmental loads in trigeneration systems for the residential–commercial sector. In addition, the possibilities of purchase/sale of electricity with the support of an auxiliary boiler and waste of part of the cogenerated heat were also considered. Economic and environmental costs were determined for all internal flows and final products, and in different operation modes, through the application of the thermoeconomic analysis methodology. The allocation proposal considered that environmental loads of the cogeneration module were distributed among the consumers of the final products, resulting in overall reduced emissions derived from the combined production. Such reductions were evaluated in proportion to the emissions via conventional systems.

The allocation rules proposed herein provided values coherent with the objective of benefitting the consumers of the energy services produced by an optimized and efficient trigeneration system; the benefit is a more efficient and environmentally friendly concurrent production in comparison to obtaining each energy service separately through conventional systems. The benefits corresponding to the sale of

electricity and the inefficiencies associated with the waste of heat were allocated rationally and equally among the cogenerated products (coproducts).

Allocation of costs (and consequently, environmental loads) in cogeneration and trigeneration systems is important because the adequate allocation of resources is fundamental to attribute the correct share of costs (or CO_2 emissions) to each energy service. A key aspect in the acceptance and success of trigeneration systems (seen as more complex but more efficient) by the users is that no unfair share of resources occurs. If the consumer assesses that the allocation was fair, the buy-in is more likely to occur.

The allocation of environmental loads will put a 'tag' or '*label*' on energy services produced, and the consumer will be empowered to discriminate between CO_2-intensive energy services and those more compatible with environmental objectives. Eco-labeling is an effective way of informing customers about the environmental impacts of selected products, and the choices they can make (IISD 2012). By knowing the environmental burden associated with the consumption of electricity, heat, and coolth, the consumer will be able to make an informed decision on whether to consume or not the energy services. The importance of the allocation proposal made herein is to make environmental information available to the consumers to promote the consumption of environmentally friendly energy services, such as the ones provided by trigeneration systems. An added benefit is that while being low in CO_2 emissions, the energy services are also low-cost when compared to conventional production. By empowering customers (and manufacturers) to make environmentally supportive decisions, the need for regulation can be kept to a minimum. This is beneficial to both government and industry (IISD 2012).

It was herein demonstrated how the benefits of trigeneration can be equally shared between users and how an adequate allocation of economic costs and environmental loads allows for a more efficient, economic, and environmentally friendly consumption and production of energy services.

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